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USE OF LASER SOUNDING TO DETERMINE CERTAIN ATMOSPHERIC CHARACTERISTICS

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Translation of: "Primeneniye Lazernoy Lokatsii Opredeleniya Nekotorykh Kharakteristik Atmosfery," Meteorologiya i Gidrologiya, Number 4, April 1974, pp. 80-85

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16. Abstract

Experimental results of atmospheric sounding by laser locator at wavelengths of 694.3 and 1,060 nm are presented. Total reverse dispersion profiles were obtained; the sounding data at nacreous cloud altitude compares favorably with other LIDAR measurements.

Data was processed from dual-frequency sounding for signal distribution, determined by reverse molecular and aerosol dispersion. Atmospheric density is computed by reverse molecular dispersion.

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USE OF LASER SOUNDING TO DETERMINE CERTAIN ATMOSPHERIC CHARACTERISTICS[1]

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With lower sounding of a cloudless atmosphere and low reception angles, in practice the dispersed signal is formed as a result of a single dispersion in the dispersing centers situated along the propagation path of the laser beam [3]. In approximation of the single dispersion, the intensity of the back-scattered signal is determined by the following expression: /80*

$$n(\Delta z) = N_0 S K \eta \beta(z) \varkappa_\pi(z) z^{-2} \Delta z \exp\left[-2\int_0^z \varepsilon(z)\,dz\right], \qquad (1)$$

where n - average number of photoelectrons in the signal received from one operation of the device from an atmospheric altitude z at an averaging interval Δz;

N_0 - number of photons radiated by the laser;

S - area of the receiving antenna;

η - quantum efficiency of the photoreceiver;

K - coefficient allowing for loss in the receiving and transmitting optical antennas;

ε - coefficient of attenuation; /81

β - coefficient of total dispersion;

$\varkappa_\pi$ - dispersion indicatrix at angle π.

Physical characteristics of the medium researched in the equation (1) are the coefficient of total dispersion, dispersion indicatrix, and the coefficient of attenuation. Generally, during the processing of experimental data, it is considered that the coefficient of attenuation is determined only by dispersion, inasmuch as the effects of absorption by aerosol in the visible range cannot be considered [1], and absorption by other atmospheric gases is eliminated by the

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appropriate selection of wavelength by the laser. By introducing beforehand the backscatter indicatrix, the equation (1) can be employed to solve relatively the coefficient of reverse dispersion, using the method of successive strata [4]. When using a signal dispersed by the atmosphere at the same wavelength as the laser radiation, and with no dispersion resonance effects present, the coefficient of reverse dispersion is equal to:

$$\sigma_\pi(z) = \beta_A(z)\varkappa_{\pi A}(z) + \beta_M(z)\varkappa_{\pi M}(z), \tag{2}$$

where β_A and β_M — volumetric coefficients of aerosol and molecular dispersion and x_π and $x_{\pi M}$ — "back" dispersion indicatrices by aerosol and dispersion at fluctuating molecular density. Molecular dispersion indicatrix is known and equal to $\frac{3}{8\pi}$, but the dispersion indicatrix by aerosol, just as coefficient of aerosol dispersion, may vary widely, contingent upon the distribution of particles by dimension, the number of particles, and their composition. Consequently, the sum indicatrix may be known only approximately, and its input into the calculation in many cases will lead to significant error [2].

Optimum results can be achieved if the method for determining the coefficient of dispersion is established in the following manner. The entire sounding route must be spaced on a stratum of such an altitude span as to consider the "back" dispersion indicatrix unchanged in the two neighboring strata. It is further to be considered that the volumetric dispersion coefficient change in these neighboring strata is the same. In the sounding of weakly dispersed media, for example, a cloudless atmosphere, these conditions are not difficult to achieve, inasmuch as the change of atmospheric dispersal properties takes place quite slowly. In this case, the equation (1) for the two neighboring (adjacent) strata is written in the form

$$\begin{aligned} n_1(\Delta z) &= N_0 SK\eta(\beta_0 - \Delta\beta)\varkappa_\pi(\Delta z) z^{-2}\Delta z_1 \exp\left[-2\int_0^z \beta(z)\,dz\right] \\ n_2(\Delta z) &= N_0 SK\eta(\beta_0 - 2\Delta\beta)\varkappa_\pi(\Delta z)(z+\Delta z_1)^{-2}\Delta z_2 \times \\ &\times \exp\left[-2\int_0^z \beta(z)\,dz\right]\exp(-2\Delta z_1\cdot\Delta\beta), \end{aligned} \tag{3}$$

where z – distance to the nearest stratum from the locator Δz, and β_0 – coefficient of volumetric dispersion in the stratum Δz_0. Integral attenuation $\exp\left[-2\int_0^z \beta(z)\,dz\right]$ and β_0 measured by sounding of stratum Δz_0 vertically and at an angle of 40° to the vertical.

Given the horizontal homogeneity of the atmosphere the following can be noted:

$$\ln\left[\exp\left(-2\int_0^z \beta(z)\,dz\right)\right]=\frac{\ln\left(\sec^2\theta\,\frac{n_2}{n_1}\right)}{1-\sec\theta}. \qquad (4)$$

Here n_1 and n_2 – numbers of signal photoelectrons, received from altitude z_0 in stratum Δz_0 during the sounding of this stratum vertically and at an angle of 40° to the vertical.

In Table 1, according to experimental measurements on the wavelength of a ruby laser, calculated values for integral attenuation to altitudes of 5 and 10 km are presented.

TABLE 1. INTEGRAL ATTENTUATION VALUES FOR LASER BEAMS BY ATMOSPHERE FOR WAVELENGTHS OF THE RUBY LASER

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Altitude, km	Θ=40°		Θ=0°		Integral Attenuation
	Distance, km	Intensity, photon	Distance, km	Intensity, photon	
5	6,5	$2,7\cdot10^5$	5	$0,35\cdot10^6$	0,39
10	13	$3,3\cdot10^4$	10	$4,39\cdot10^4$	0,32

Commas indicate decimal points.

It can be noted that the primary attenuation of the laser emission takes place in the lower troposphere, up to 5 km. The change in attenuation from 5 to 10 km occurs within the experiment error limit for a standard atmosphere. This necessitates introducing a correction for attenuation according to standard atmosphere at altitudes in excess of 10 km. By using the measurements of the values n_1 and n_2, etc., from the equations (3), total volumetric and reverse coefficients of dispersion were calculated. To reduce error associated with replacing a real, smooth coefficient of dispersion curve by a graduated

one, the calculations was repeated several times with a change of strata altitude of $\pm \frac{1}{2} \Delta z$.

In this manner, a simple wave sounding of the atmosphere permits the determination of the coefficient of dispersion vertical profile. This can be used to solve problems such as locating aerosol strata, the detailed study of their fine structure, spatial and temporal variations, and also in determining transparency of the atmosphere. But the single-wave sounding, with the exception of the Doppler resonance and combination methods, does not permit determination of thermodynamic atmospheric parameters, inasmuch as it does not provide for the distribution of the sum coefficient of dispersion upon molecular and aerosol constituents. To effect such a distribution, an additional experiment complication is required. Specifically, the authors suggest the method of dual-wave atmospheric sounding for this purpose.

We will examine a situation of simultaneous locations of the atmosphere on two wavelengths. For each of the wavelengths, the following may be noted:

$$n_{\lambda_1}(\Delta z) = N_{01} SK_1 \eta_1 \beta_1(z) \varkappa_{\pi 1}(z) z_{n-1}^{-2} \Delta z_n \exp\left[-2\int_0^z \beta(z)\, dz\right], \quad (5)$$

$$n_{\lambda_2}(\Delta z) = N_{02} SK_2 \eta_2 \beta_2(z) \varkappa_{\pi 2}(z) z_{n-1}^{-2} \Delta z_n \exp\left[-2\int_0^z \beta(z) dz\right]. \quad (6)$$

We suggest that from these equations examined by the above method, two profiles for the coefficients of sum dispersion β_1 and β_2 have been determined.

$$\beta_1(z) = \beta_{1M}(z) + \beta_{1A}(z), \quad \beta_2(z) = \beta_{2M}(z) + \beta_{2A}(z). \quad (7)$$

Here β_M and β_A — coefficients of molecular and aerosol dispersion.

It is known that $\frac{\beta_{1A}}{\beta_{2A}} = P$. This ratio characterizes the frequency dependence of the coefficients of aerosol dispersion, and for the actual atmosphere may vary widely.

After simple conversions from (7) we obtain: $\frac{\beta_{1M}}{\beta_{2M}} = \frac{\lambda_2^4}{\lambda_1^4}$, $\frac{\beta_{1A}}{\beta_{2A}} = P$. /83

(8)

$$\beta_{1\,A}(z)=\frac{P}{\frac{\lambda_2^4}{\lambda_1^4}-P}\left[\frac{\lambda_2^4}{\lambda_1^4}\beta_2(z)-\beta_1(z)\right],\qquad \beta_{2\,A}(z)=\frac{\frac{\lambda_2^4}{\lambda_1^4}\beta_2(z)-\beta_1(z)}{\frac{\lambda_2^4}{\lambda_1^4}-P}; \tag{9}$$

The parameter P in these expressions is unknown. To determine it, we make the conversions of (5) and (6).

$$\ln n_{\lambda_1}=\ln\left(N_{01}K_1S\eta_1 z_{n-1}^{-2}\Delta z_n\right)+\ln\sigma_{1\pi}-2\int_0^z\beta_1(z)\,dz, \tag{10}$$

$$\ln n_{\lambda_2}=\ln\left(N_{02}K_2S\eta_2 z_{n-1}^{-2}\Delta z_n\right)+\ln\sigma_{2\pi}-2\int_0^z\beta_2(z)\,dz. \tag{11}$$

We assume

$$\int_0^{z_n}\beta(z)\,dz=\int_0^{z_{n-1}}\beta(z)\,dz+\int_{z_{n-1}}^{z_n}\beta_A(z)\,dz+\int_{z_{n-1}}^{z_n}\beta_M(z)\,dz. \tag{12}$$

Then from (10)-(11) we have

$$2\int_{z_{n-1}}^{z_n}\beta_{1\,A}(z)\,dz=\ln\left(N_{01}K_1S\eta_1 z_{n-1}^{-2}\Delta z_n\right)+\ln\sigma_{1\,n}-\ln n_{\lambda_1}-$$

$$-2\int_0^{z_{n-1}}\beta_1(z)\,dz-2\int_{z_{n-1}}^{z_n}\beta_{1\,M}(z)\,dz, \tag{13}$$

$$2\int_{z_{n-1}}^{z_n}\beta_{2\,A}(z)\,dz=\ln\left(N_{02}K_2S\eta_2 z_{n-1}^{-2}\Delta z_n\right)+\ln\sigma_{2\pi}-\ln n_{\lambda_2}-2\int_0^{z_{n-1}}\beta_2(z)\,dz-2\int_{z_{n-1}}^{z_n}\beta_{2\,M}(z)\,dz. \tag{14}$$

We assume that

$$\frac{2\int_{z_{n-1}}^{z_n}\beta_{1\,A}(z)\,dz}{2\int_{z_{n-1}}^{z_n}\beta_{2\,A}(z)\,dz}=P. \tag{15}$$

The expression (15) is correct, if in the atmospheric stratum Δz the frequency dependence of the coefficient of aerosol dispersion is unchanged. In practice, such a stratum expanse can always be selected, and in the limiting situation, this would be the element stratum (altitude averaging interval). /84

Then with calculation (13)-(15) we have:

$$P = \frac{\ln\left(N_{0\,1} K_1 \eta_1 S z_{n-1}^{-2} \Delta z_n\right) - \ln n_{\lambda_1} + \ln \sigma_{1\,\pi} - \\ \ln\left(N_{0\,2} K_2 \eta_2 S z_{n-1}^{-2} \Delta z_n\right) - \ln n_{\lambda_2} + \ln \sigma_{2\,\pi} - \\ -2\int_0^{z_{n-1}} \beta_1(z)\,dz - 2\int_{z_{n-1}}^{z_n} \beta_{1\,M}(z)\,dz \\ \rightarrow \frac{}{-2\int_0^{z_{n-1}} \beta_2(z)\,dz - 2\int_{z_{n-1}}^{z_n} \beta_{2\,M}(z)\,dz} \rightarrow \quad (16)$$

In this manner, using expressions (8), (9), and (16), distribution of the /85
sum coefficients upon molecular and aerosol constituents is achieved. In the two-frequency atmospheric soundings carried out, when strong gradients in coefficients of dispersion were not observed, the averaging interval was selected equal to 0.25-0.5 km, and it was considered that in the altitude range of 0.75-1.5 km the condition (15) was effected with sufficient exactness. Values input for Δz and $3\Delta z$ were selected from experimental conditions, in which the increasing of the signal from the stratum above and adjacent was greater than the experiment error. In computing the third stratum, for which expression (16) was established, provision in the calculation scheme was made for the statistical spread observed during the sounding to be somewhat increased.

Results of the experiment conducted on vertical sounding of the atmosphere are presented in Figures 1-3. Figure 1 pertains to atmospheric sounding at a wavelength of 694.3 nm. In calculating the coefficient of sum dispersion for altotudes greater than 5 km, for the value of integral attenuation, taken from Table 2, correction for standard atmosphere was introduced. For altitudes up to 5 km, calculations were carried out by the method advanced above.

At altitudes of 18-24 km a high stability of aerosol particle strata was observed.

Figure 3 contains comparisons of several curves characterizing the behavior of coefficients of dispersion at these altitudes, based on data obtained at different times by various groups of researchers.

Figure 3 refers to the simultaneous sounding of the atmosphere on wavelengths 694.3 and 1,060 nm. It is interesting to note the characteristic relationship between the coefficients of sum dispersions on the two wavelengths.

In the lower troposphere, the ratio of the coefficient of sum dispersion for wavelengths of the ruby laser to the coefficient for the neodymium laser is approximately equal to 3. With an increase in altitude the ratio increases, and at an altitude of 10 km is equal to 4. This indicates that at the altitudes given, the aerosol content of the atmosphere diminishes, even more significant, inasmuch as in the absence of aerosol at the wavelengths given, the ratio of coefficients of reverse dispersion would be equal to 5, corresponding to the ratio of signal intensities during molecular dispersion to the ratio of integral attenuation up to the atmospheric altitudes examined.

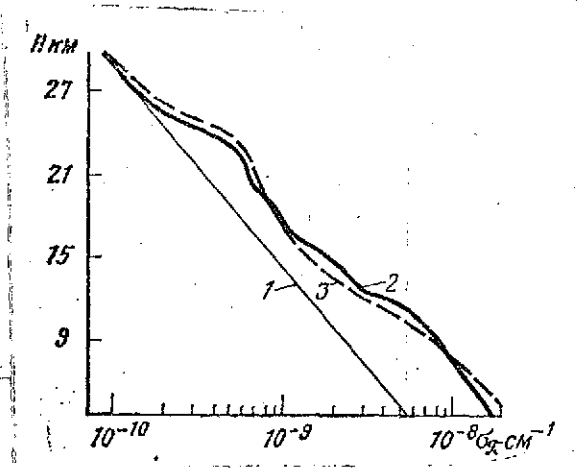

Figure 1. Results of Atmospheric Laser Sounding at Wavelength of 694.3 nm (Karadag, Crimea, 45°C, 1972). 1, Standard atmosphere SIRA-71; 2, method of laboratory graduation; 3, calibration method for signal from 30 km. Average for 250 pulses.

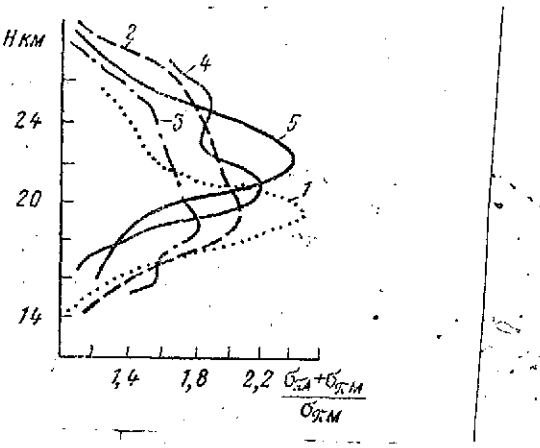

Figure 2. Relationship of Total Reverse Dispersion to Molecular. 1, Fiokko (Boston, Massachusetts); 2, Wright (Kingston, West Indies); 3, George Watson (Mt. Sacramento, New Mexico); 4, authors of article (Karadag), 1971; 5, authors of article, 1972. Average for 250 pulses.

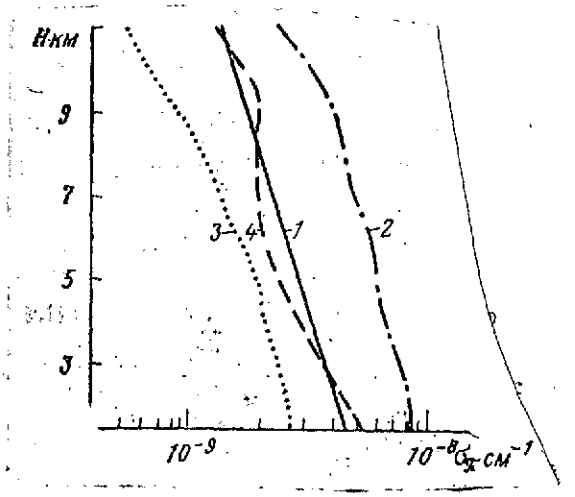

Figure 3. Results of Two-Frequency Atmospheric Soundings. 1, Standard atmosphere SIRA-71; 2, total reverse dispersion, 1,060 nm; 3, total reverse dispersion 694.3 nm, calculated according to the suggested scheme. Average for 30 pulses.

Results of the distribution of the coefficient of sum dispersion upon molecular and aerosol constituents are also presented in Figure 3. It can be noted that within the limits of equipment error, the experimentally determined profile of molecular dispersion conforms with the altitude dependence of this coefficient for a standard atmosphere. Inasmuch as the maximum measurements error reaches 30-40%, the further perfecting of equipment and experimental methodology is necessary. However, the method suggested for the distribution of aerosol and molecular constituents of the dispersed signal would appear to be most simply realized.

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